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Strategy-making for a proactive distribution company in the real-time market with demand response

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HIGHLIGHTS

- A proactive DISCO (PDISCO) is presented to trade in the real-time market.
- A demand response definition is presented.
- A bi-level model is proposed to illustrate the strategy-making problem of the PDISCO.
- Continuous trading strategies (offers and bids) are achieved by PDISCO.

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ABSTRACT

This paper proposes a methodology to optimize the trading strategies of a proactive distribution company (PDISCO) in the real-time market by mobilizing the demand response. Each distribution-level demand is considered as an elastic one. To capture the interrelation between the PDISCO and the real-time market, a bi-level model is presented for the PDISCO to render continuous offers and bids strategically. The upper-level problem expresses the PDISCO's profit maximization, while the lower-level problem minimizes the operation cost of the transmission-level real-time market. To solve the proposed model, a primal-dual approach is used to translate this bi-level model into a single-level mathematical program with equilibrium constraints. Results of case studies are reported to show the effectiveness of the proposed model.
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1. Introduction

A low-cost and high-efficiency demand response (DR) has been recognized worldwide as a valuable resource [1,2]. Because DR is dispersed and highly sensitive to the real-time price [3,4], an aggregator is commonly considered as a third entity to launch direct control or incentive schemes to manage individual DRs [5]. As addressed in the New York Reforming Energy Vision (NY REV) [6], the concept of Distributed System Platform Provider (DSPP) is raised to promote the utilization of distributed energy resources (DERs) deployed in the distribution-level (DL) network. To enhance the transmission and distribution trading efficiency, the distribution company (DISCO) can bee seen as a DSPP, while DR [7,8], distributed generation (DG) [9], and microgrids (MGs) [10] can be considered as the major flexibility providers [11–13]. In practice, the DISCO has full knowledge of both the transmission-level (TL) markets and the DL operations. For this reason, the DISCO is a superior representation [14,15] of the DR resources available to trade in the TL market.

The well-developed smart grid technology [16,17] that exists today turns bidirectional power exchanging between the distribution and transmission networks into reality. As a profit-driven company, to participate in the real-time market, at each time t, the DISCO has to downwardly optimize the DR portfolio and upwardly hand over a trading strategy (offer/bid) to the wholesale market for profit maximization. The continuous strategic behaviors of the DISCO result in a dual role in the market, i.e., as an active

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Nomenclature

Sets and Indices

i, j, B^{DS} n, m, B^{TS}	index and set of distribution-level (DL) and transmission-level (TL) buses, respectively
ij, Λ^{DS} nm, Λ^{TS}	index and set of DL feeders and TL lines, respectively
l, L d, D	index and set of DL demands and TL demands, respectively
g, G	index and set of TL generators
t, T	index and set of time periods (e.g., hours per day)
$\mathcal{M}_L, \mathcal{M}_D$	mapping of the set of DL/TL demands onto the set of DL/TL buses, respectively
$\mathcal{M}_G$	mapping of the set of TL generators onto the set of TL buses

Variables

r_{tg}^{UP}, r_{tg}^{DN}	real-time up and down regulation power of generator g at time t [MW], [MW]
$P_{tl}^{DRT}, Q_{tl}^{DRT}$	real-time offering/bidding quantities of the PDISCO at time t [MW], [MVar]
P_{td}^{ST}	TL load-shedding of demand d at time t [MW]
P_{tl}^{SD}, Q_{tl}^{SD}	active and reactive power of DS load-shedding for demand l at time t [MW], [MVar]
Q_{ti}^{C}	real-time reactive power from DL shunt compensator at bus i at time t [MVar]
$P_{t,ij}^{Flow}, Q_{t,ij}^{Flow}$	real-time active and reactive power flows through DL feeder ij at time t [MW], [MVar]
V_{ti}	real-time voltage magnitude of DL bus i at time t [kV]
λ_{tl}^{DRT}	real-time offering/bidding price of the PDISCO at time t [€/MW]
α_{tl}	elasticity factor of DL demand l at time t
θ_{tn}	real-time voltage angle of TL bus n at time t
δ_{ti}	real-time voltage angle of DL bus i at time t

Parameters

c_g^{UP}, c_g^{DN}	real-time up and down regulation cost of TL generator g [€/MW], [€/MW]
P_{tg}^{G}	day-ahead offer of TL generator g at time t [MW]
R_{tg}^{UP}, R_{tg}^{DN}	day-ahead up and down regulation reserve capacities of TL generator g at time t [MW], [MW]
$P_{td}^{TSD}, P_{td}^{TSR}$	day-ahead and real-time consumption of TL demand d at time t [MW], [MW]
$P_{tl}^{DSD}, Q_{tl}^{DSD}$	day-ahead consumption of DL demand l at time t [MW], [MVar]
$\overline{P}^{DS}$	active power injection limit for the PDISCO [MW]
$\overline{P}_{nm}^{TS}$	capacity limit of each TL line nm [MW]
$\overline{S}, \overline{S}_{ij}$	capacity limits of the DL main substation and each DL feeder ij [MVA], [MVA]
$\underline{Q}_i^C, \overline{Q}_i^C$	reactive power limits of the DL shunt compensator at bus i [MVar], [MVar]
$\underline{V}_i, \overline{V}_i$	limits of voltage magnitude at DL bus i [kV], [kV]
B_{nm}	susceptance of the TL line nm [S]
G_{ij}, B_{ij}, b_{ij}	conductance, susceptance, and charging susceptance of the DL feeder ij [S], [S], [S]
λ_t^{DSD}	DL sale price at time t [€/MW]
λ_{tn}^{DA}	day-ahead locational marginal price (LMP) at TL bus n at time t [€/MW]
$\lambda_t^{ST}, \lambda_t^{SD}$	TL/DL load-shedding price at time t [€/MW], [€/MW]
Γ	elasticity limit of each DL demand
τ_i	transformer tap ratio at DL bus i
ρ	consumption control factor

producer when providing offers, but as an active consumer when submitting bids. Accordingly, the trading between the DISCO and the TL market features in a bidirectional transaction. To characterize this type of DISCO, we define it as a proactive DISCO (PDISCO) in this paper.

Note that the PDISCO's trading strategies are correlated with the market's outcomes. Thus, the PDISCO trading within the market can be formulated as a bi-level game-theoretic model. The lower-level problem is about the real-time market clearing based on DC power flow, aiming to minimize the TL operation cost. The upper-level problem is to maximize the PDISCO's profit by AC power flow constraints, with the PDISCO seeking to render strategic offers/bids. It is also worth noting that the lower-level problem is linear and thus convex, while the upper-level problem is non-linear and non-convex. A primal-dual approach [18] can be used to reformulate the proposed bi-level model as a solvable mathematical program with equilibrium constraints (MPEC).

Some papers pertaining to DISCO trading in the TL markets are available in the literature. In the day-ahead market, a bi-level model is proposed in [19] to address a DISCO's operation decisions with DGs and interruptible loads (ILs). However, the DISCO's offers or bids are not included in the market's objective. A hierarchical market structure is provided in [20] to depict the interaction between the distribution and transmission networks. On the basis of this structure, a bi-level model is presented, while the locational marginal prices (LMPs) are not endogenously obtained by the power flow constraints. To address a DL market framework by incorporation into the TL market, a bi-level model is proposed for a load serving entity (LSE) to manage aggregator-based DR through a dynamic pricing mechanism [21]. In particular, DC power flow is used to model the distribution network. For simplicity, the TL market performance and physical constraints are not fully considered. At the day-ahead stage, a static bi-level model [22] is presented for the DISCO's make energy acquisitions from the TL wholesale market, ILs and dispatchable DGs. A multi-period bi-level model is proposed and further developed in [23], to indicate the market impacts of the ILs and the DISCO-owned DGs. However, the network constraints are ignored.

From differing perspectives, bi-level modeling is increasingly used to elaborate the trading strategies in markets [24]. In a pool market, a bi-level model is proposed in [25] for a strategic producer to use against its rivals. A stage-based stochastic bi-level model is presented in [26] to derive the offering strategy for a wind-power producer that is involved in both the day-ahead market and the balancing market. From the consumer side, a multi-period bilevel model [27] is proposed to minimize the payment in Pool markets according to LMPs. To make up strategic bidding curves for a large consumer, a bi-level model is further reported in [28] to minimize its day-ahead payment. The strategic operation between the DL operator and MGs is implemented by a bi-level model in [29]. In addition, the authors in [30] propose a bi-level model to handle multiple MGs in a competitive environment.

On the other hand, to enable flexible demand trading in existing electricity markets, load shifting is achieved by a Lagrangian relaxation-based heuristic approach [31]. With the presented market mechanism, the DR performance is further validated and discussed by [32]. The network constraints are excluded by the model. From the management perspective, a contract-based cluster [33] is proposed to facilitate elastic demands to purchase or sell energy according to the interactions between DG and the main

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